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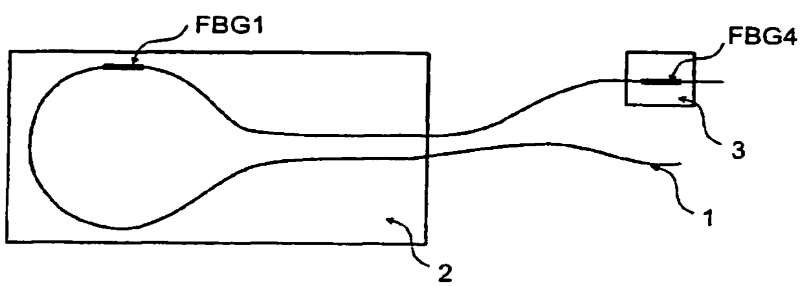
(54) Title: FIBER OPTIC SENSOR PACKAGE



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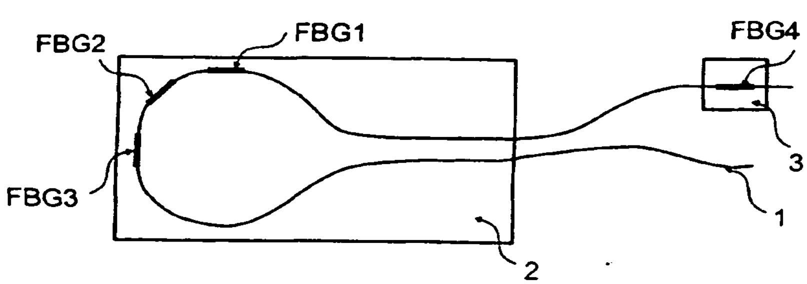

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(57) Abstract: This invention relates to a fiber optic strain sensor for sensing plane strain in at least one direction, as well as a sensor package and related systems. The strain sensor comprises an optical fiber (1) including at least one Bragg grating (FBG1) responsive to mechanically induced strain, the strain responsive Bragg grating(s) being bonded to a polymer film (2) with a defined direction on the film with respect to one outer edge of the film, said fiber forming an essentially circular loop on the film, said at least one Bragg grating being positioned in a linear portion of said loop. The invention also relates to a temperature sensor (3) especially for use in relation to thestrain sensors.

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Declaration under Rule 4.17:

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FIBER OPTIC SENSOR PACKAGE

TECHNICAL FIELD

The invention relates to the field of measuring strain and/or temperatures on a surface. More specifically it relates to a fiber optic Bragg grating strain sensor for sensing strain in at least one direction, e.g. on large structures such as ships, bridges and oil drilling and production rigs.

BACKGROUND OF THE INVENTION

In many strain and stress monitoring applications fiber optic strain sensors have advantageous properties compared to electrical sensors. However, the optical fiber is vulnerable to mechanical impact and must be packaged to ensure longevity in practical applications. The present invention provides means for packaging a fiber optic strain sensor to protect the sensitive portion of the sensor and to provide the sensor with a rugged connecting cable.

In strain measurement systems it is imperative to know the precise orientation of the strain sensor with respect to the structure being monitored, and it is beneficial to have the sensors prepackaged in a way that eases installation in the field by providing edges to orient by that are well defined with respect to the sensor's orientation. In some cases the application calls for measurement of uniaxial strain in which case a single strain sensor is used. In other cases one needs a more comprehensive characterization of the in-plane stress of the surface, and this calls for bi- or tri-directional strain measurement. In case of multi-directional strain measurements it is necessary to have the different strain sensors oriented in a well-defined pattern with respect to each other.

Multi-directional strain sensing has conventionally been done using a rosette of electrical strain gauges with measurement directions spaced angularly by 45 or 60 degrees. An example of an embodiment of such an electrical strain gauge rosette is shown in US 5.726.744, WO 00/28294 and US 6.125.216.

Fiber optic rosettes have been proposed that have different geometrical characteristics. One known embodiment is shown in WO 00/28294 in which three fiber Bragg gratings are incorporated in a fiber which is laid out in a bow-tie pattern. This embodiment has the disadvantage that the fiber crosses over itself. It is well known in the field that such a fiber crossing is a weak point where the fiber is likely to break if subjected to pressure.

A different geometry has been suggested in US 6125216 in which the fiber is laid out in a triangular pattern with the Bragg gratings placed along the straight edges of the triangle as. This embodiment is placed close to a fiber end, and thus prevents the proposed rosette from being connected in a serial manner with other sensors. It is further common knowledge in the field that tight bends on optical fibers leads to optical losses as well as reduced lifetime due to cracking in the glass, which over time may develop to a total break of the fiber. Thus it is desirable to avoid bends with a radius of less than 1-2cm.

One strategy for allowing tight bends has been developed in WO 00/28294. Here the inventors propose using a similar triangular fiber pattern as in the above mentioned patent, but using fiber that has been tapered between the fiber Bragg gratings. While this solves the problem of optical losses, it leaves the optical fiber substantially mechanically weakened at the tapers.

A strategy that avoids tight bends has been described in US patent 5,726,744, in which the inventors propose laying the fiber out along a circular path. However, we can demonstrate that bending a strain sensing Bragg grating will lead to cross-sensitivity, in the sense that part of the responsive length of the grating will pick up strain orthogonal to the intended measurement direction. This cross-sensitivity can be calculated in the following way for an unapodized grating of length 2b following an arc of radius R. For any point along the grating the local contribution to the strain response in the x-direction is $\cos\theta$, while the cross-sensitivity response is $\sin\theta$. Integrating these expressions over the length of the grating we find

$$i_x = 2\varepsilon_x \int_0^{b/R} \cos\theta d\theta = 2\varepsilon_x \sin\frac{b}{R}$$

$$i_y = 2\varepsilon_y \int_0^{b/R} \sin\theta d\theta = 2\varepsilon_y \left(1-\cos\frac{b}{R}\right)$$

where we have integrated along the arc from $\theta = 0$ to $\theta = b/R$ to find the contribution from one half of the grating length, multiplying by two to find the total contribution assuming symmetry. The measured value will be the sum of the two contributions. We can find a simple expression for the effect of bending if we divide i_y/i_x, substituting $b/R=2\phi$ and further substituting $1-\cos 2\phi = 2\sin^2\phi$ and $\sin 2\phi = 2\sin\phi\cos\phi$. Then $\frac{i_y}{i_x} = \frac{2\varepsilon_y(1-\cos 2\phi)}{2\varepsilon_x \sin 2\phi} = \frac{\varepsilon_y}{\varepsilon_x}\frac{\sin^2\phi}{\sin\phi\cos\phi} = \frac{\varepsilon_y}{\varepsilon_x}\tan\frac{b}{2R}$.

Inserting common values for grating length and bending radii, we find that this effect will have potentially large consequences for measurement of small strains when there are large perpendicular strains present. It is therefore important for the performance of Bragg grating strain sensors that the gratings are mounted in a straight line.

Due to the thermal response of the sensor itself and the thermal expansion of the structures on which the sensors are mounted it is generally desirable to measure temperature or at least provide a measure for the sensor's inherent thermal response, thus to enable thermally compensated strain values. This is conveniently done using a strain isolated Bragg grating multiplexed onto the same fiber as the strain sensor(s). Techniques for strain isolating a grating near the end of an optical fiber was described by Haran et al. in 6,125,216. In order to multiplex several rosettes onto a single fiber it is necessary to form an in-line temperature sensor, i.e. a package from which both fiber ends are available for splicing.

The object of the present invention is to provide a package for fiber Bragg grating strain sensors that eases installation in relatively harsh environments, that can easily be aligned to axes in the structure and which may be connected to an interrogation device via a rugged fiber optic cable. Further the package provides a means for pre-orienting the strain sensitive Bragg gratings of a rosette with an angular spacing of e.g. 45 or 60

degrees without introducing sharp bends or crossings of the fiber, which would reduce longevity of the sensors, while at the same time avoiding the introduction of cross-sensitivity by bending the Bragg grating. A typical application for such sensors is in structural health monitoring of large structures such as ships, bridges and oil drilling and production rigs.

SUMMARY OF THE INVENTION

According to the present invention an optical fiber strain sensor is provided having one or more strain sensitive Bragg gratings incorporated in a single optical fiber, which fiber is mounted on a polymer film in a nearly circular path, the path deviating from a circle for the length of the Bragg gratings which are mounted in a straight line. The invention is characterized as stated in the independent claims.

According to a preferred embodiment of the invention the optical fiber is provided with a strain isolated Bragg grating for sensing the temperature and thus providing information needed to compensate the strain values measured by the strain sensitive Bragg grating(s) for thermal effects.

In one embodiment the strain isolation is provided by mounting the temperature sensing Bragg grating in a loop on the fiber, which is placed in a groove between two rigid discs. The exits from the grooves should be sealed.

In a second embodiment the strain isolation is provided by mounting the temperature sensing Bragg grating on a rigid stiffener, the stiffener and the fiber Bragg grating further enclosed in a material with low mechanical stiffness to prevent stress to be transferred to the assembly of fiber Bragg grating and stiffener.

According to a further aspect of the present invention a sensor package for optical fiber strain sensors suited for relatively harsh environments is provided in which the optical fiber is spliced to a rugged cable, and the cable end, the splices, the strain isolation package and one end of the polymer film with the fiber Bragg grating strain sensor incorporated in a stress relief package cast from a flexible polymer. Preferably the stress

relief package has a plane bottom surface to facilitate fixture to the surface of a structure.

The stress relief package may further have a thickness profile that facilitates embedding of the polymer film containing the strain sensors and the stress relief package under a fiber reinforced polymer layer for added mechanical protection.

In a practical application of the sensor package it would be attached to the surface of a structure. One end of the optical fiber in the cable should be connected to a system for illumination and signal interrogation. The signals from the Bragg gratings could be interpreted in a number of fashions such as time or coherence multiplexing, but the preferred embodiment incorporates wavelength multiplexing of the Bragg gratings on the fiber. The other end of the optical fiber could be spliced to a second sensor package with Bragg gratings at compatible wavelengths.

The interrogation system should be able to interpret the signal from the strain and temperature sensors and from this information compensate the strain values for the inherent temperature response of the Bragg gratings and possibly the thermal expansion of the structure.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A Optical fiber 1 with Bragg grating FBG1 mounted on a polymer film 2, the Bragg grating being mounted along a straight line, and a second Bragg grating FBG4 being isolated from strain in a package

Figure 1B Optical fiber 1 with Bragg gratings FBG1-FBG3 forming a rosette mounted on a polymer film 2, the Bragg gratings being mounted along a straight line, and a fourth Bragg grating FBG4 being isolated from strain in a package

Figure 2A Strain isolated Bragg grating in a loop

Figure 2B Strain isolated Bragg grating on a stiffener

Figure 3 Film with strain sensing Bragg gratings partially incorporated in a cast stress relief from which a rugged fiber optic cable emerges.

Figure 4 Diagrammatic plan of a sensor system with several sensor packages connected to a light source and a computer-controlled interrogation unit.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1A shows an optical fiber 1 incorporating a Bragg grating FBG1 responsive to strain mounted on a polymer film 2, e.g. made from polyimide. The optical fiber follows a circular path except at the location of the Bragg grating, which is attached to the film in a straight fashion so as to avoid variations in the grating response to strain along the grating length. As mentioned above the minimum radius of the curvature of the fiber should be larger than 1-2 cm, though short duration applications may be concidered in which the radius may be allowed to be less. On the same fiber is optionally incorporated a second grating FBG4 which is placed in a package 3 that works to isolate the grating from strain with the purpose of providing a temperature measurement that can be used to compensate for the thermal signal measured by the strain responsive grating.

Figure 1B shows a second embodiment of the invention wherein an optical fiber 1 incorporating three Bragg gratings FBG1-FBG3 responsive to strain mounted on a polymer film 2. The optical fiber follows a circular path except at the location of each of the Bragg gratings, which are mounted in a straight fashion with a defined angle with respect to each other. Thus the three gratings form a rosette applicable to measuring the state of strain in a surface. On the same fiber is incorporated a fourth grating FBG4 mounted in a package 3 that works to isolate the grating from strain and provide a temperature measurement that can be used to compensated for the thermal component of the signal from FBG1-FBG3.

In addition to the solutions shown in figures 1A and 1B an embodiment with two sensors is possible, e.g. with a relative angle of 45 or 60 degrees or with perpendicular orientations, for sensing strain along the two axes. An important aspect of both solutions is that the orientation of the gratings relative to at least one of the edges of the

foil 2 should be known, so as to ease the positioning of the sensors and ensure that direction of a measured strain is correct. Also, for providing some protection for the fiber it is preferably laminated between two polymer films.

Figure 2A shows one embodiment of such a strain isolation package where a loop of the optical fiber 1 incorporating a Bragg grating FBG4 is placed in a circular groove 6 in a disc 4, the optical fiber entering and exiting the groove 6 via v-grooves 7 tangent to the groove 6. This solution secures the strain independence and provides protection from mechanical disturbances from the environment.

The groove is sealed by fixing a lid 5 over the disc 4, and capping the v-grooves 7 with a suitable sealant so as to avoid disturbances caused from fluids or gases entering the sensor as well as deterioration of the fiber sensor. The disc 4 may be made from a polymer material and have i chosen degree of flexibility so as to enable it to adapted to the surface it is to be attached to.

Figure 2B shows a second, more compact embodiment of a strain-isolation package designed to provide a reference temperature measurement. The Bragg grating FBG4 incorporated in optical fiber 1 is placed on a piece of high elastic modulus material, a stiffener, 8 and fixed to the stiffener using a high modulus adhesive 9. The high modulus stiffener is preferably made from a material with the same thermal expansion rate as the optical fiber, advantageously from fused silica. The stiffener may take many shapes, but could for instance be shaped as a rod with a v-groove or a U-profile. The optical fiber and stiffener are further encapsulated in a lower elastic modulus polymer 10, which works to reduce strain concentrations in the optical fiber at either end of the stiffener.

The solutions illustrated in figures 2A and 2B may be implemented close to a chosen number of the strain sensors or independently in a system comprising a number of strain sensors, or possibly in a dedicated system for measuring the temperatures independently of any strain sensors.

Figure 3 shows a sensor package assembly suited for real world application where an optical fiber 1 with Bragg sensors FBG1-FBG3 is mounted in a rosette pattern between two polymer films 2, the fiber further incorporating a fourth grating FBG4 in a strain-isolation package 3, which two fiber ends are spliced to a rugged cable 12. One end of the polymer film 2 and the cable are encapsulated in a cast polymer stress relief 11, which further encapsulates the strain isolation package 3. The stress relief 11 is preferably cast in a flexible and resilient polymer such as polyurethane. It has a plane surface to enable good adhesion to a surface when mounted with a suitable adhesive, and a low profile to render it suitable for surface embedding under a protective layer of fiber reinforced polymer.

The sensor package is intended for use in a multiplexed sensor system as schematically shown in Figure 4. Several sensor packages P1-P3 are mounted on a structure using a suitable adhesive for the purpose of characterizing the strain on the structure. P1-P3 are fusion spliced or otherwise optically coupled to each other forming a continuous path in the optical fiber 1 from a light source 13 via an optical coupler 16 to each of the sensor gratings incorporated in the sensor packages. The light reflected from the gratings is led via the coupler 16 to a receiver unit 14 that has the function of detecting the light and converting the raw signal to electrical signals representing the measurements made by the Bragg gratings. A person versed in the field will know that this may be done in a number of ways, such as using a scanning Fabry-Perot filter, a Mach-Zehnder interferometer or an optical spectrum analyzer. The electrical signal is passed to a signal-processing unit 15 via a suitable electrical connection 17. The signal-processing unit is conveniently a digital computer using any suitable algorithms being available.

The sensor packages in figure 4 are oriented with a known orientation with respect to each other and/or a frame of reference for maximum precision in the measurements. In order to obtain this the film or stress reliefs may be provided with at least one edge indicating the orientation of at least one sensor, e.g. by having a Bragg grating/sensing direction being parallel to a reference edge of the cast stress relief. In the case in which each sensor loop includes only one sensor the orientation of the sensors may be changed periodically or according the predicted stress direction to be measured. By comparing

the stress measured by a number of sensors in different positions the situation over a larger area, such as the hull of a ship, may be mapped.

The sensors, optical sources and receivers, as well as the rest of the equipment, are all adapted to operate at a chosen range of wavelengths, and are per se known to a person known in the art. Typically wavelengths in the range of 1550nm, and possibly in the range of 1300nm, are used, since these ranges are commonly used for telecommunication purposes and thus provides a large range of inexpensive and commercially available equipment. Also the wavelength range of the system may be adapted to the interrogation technique. As mentioned above the signals from the Bragg gratings could be interpreted by time or coherence multiplexing, but the preferred embodiment incorporates wavelength multiplexing of the Bragg gratings on the fiber thus covering a sufficiently large wavelength range to allow each Bragg sensor to have a unique Bragg wavelength in order to distinguish it from other sensors.

In addition to the interrogation system 13,14,15,16,17 illustrated in figure 4 a similar system may be provided at the other end of the sensor packages, so as to provide measurements from both sides and thus making it possible to continue monitoring the sensor packages even if the fiber is broken in one area. Alternatively both ends of the optical fiber is connected to the same interrogation system thus being able to monitor the system in both directions.

Various modifications can be made to the presented embodiments within the scope of the claims.

Claims

1. A fiber optic strain sensor for sensing plane strain in at least one direction, comprising an optical fiber including at least one Bragg grating responsive to mechanically induced strain, the strain responsive Bragg grating(s) being bonded to a polymer film with a defined direction on the film with respect to one outer edge of the film, said fiber forming an essentially circular loop on the film, said at least one Bragg grating being positioned in a linear portion of said loop, both ends of the fiber being available for connection.

2. Fiber optic strain sensor according to claim 1 wherein the optical fiber is laminated between two polymer films.

3. Fiber optic strain sensor as described in claim 1 wherein the polymer film is made from polyimide.

4. Fiber optic strain sensor according to claim 1 comprising three Bragg gratings mounted in a plane with 45 degrees angle relatively to each other.

5. Fiber optic strain sensor according to claim 1, comprising a strain isolated fiber optic temperature reference sensor.

6. A fiber optic temperature sensor comprising a Bragg grating being positioned in a loop in the fiber, which loop is placed in a circular groove between two discs and where the exits from the groove are capped with a sealant.

7. A fiber optic temperature sensor, comprising a temperature sensitive Bragg grating is affixed to a high elastic modulus material, which Bragg grating and high elastic modulus material are further encapsulated in a low elastic modulus material covering its length as well as a chosen length of additional fiber on either side.

8. A sensor package consisting of a fiber optic strain sensor mounted on a film as described in any one of claim 1-5, wherein the edge of the film where the fiber exits is incorporated in a cable stress relief cast in flexible polymer, and where a strain isolated reference grating as described is incorporated in the stress relief.

9. A sensor package according to claim 8 where the cable stress relief is cast in polyurethane.

10. A sensor package according to claim 8, wherein one Bragg grating is parallel to a reference edge of the cast stress relief.

11. A sensor package according to claim 8 wherein the sensor package is further mechanically protected on mounting on a structure by laminating the package including film and all or parts of the cast stress relief under a fiber reinforced polymer layer.

12. A sensor package according to claim 8 wherein the strain isolated reference grating is a Bragg grating being positioned in a loop in the fiber, which loop is placed in a circular groove between two discs and where the exits from the groove are capped with a sealant.

13. A sensor package according to claim 8 wherein the strain isolated reference grating is a Bragg grating is affixed to a high elastic modulus material, which Bragg grating and high elastic modulus material are further encapsulated in a low elastic modulus material covering its length as well as a chosen length of additional fiber on either side.

14. A sensor system comprising at least one strain sensor according to one of claims 1-4, and also comprising a fiber optic temperature sensor being optically coupled to at least one strain sensor, the temperature sensor functioning as a temperature reference for the strain sensor, the system being adapted for optical coupling to a light source and an optical interrogation unit, for passing wavelength information to a

computer provided with a computer program means for converting the wavelengths to strain and temperature values.

15. A sensor system comprising at least one strain sensor according to any one of claim 1-5, comprising an optical interrogation unit being positioned at at least one of the ends of said optical fiber.

16. A sensor system comprising at least one sensor package according to any one of claims 8-13, being fixed to the surface of a structure and further being connected to a light source and an interrogation unit, which is further passing wavelength information to a computer provided with a computer program means for converting the wavelengths to strain and possible temperature values.

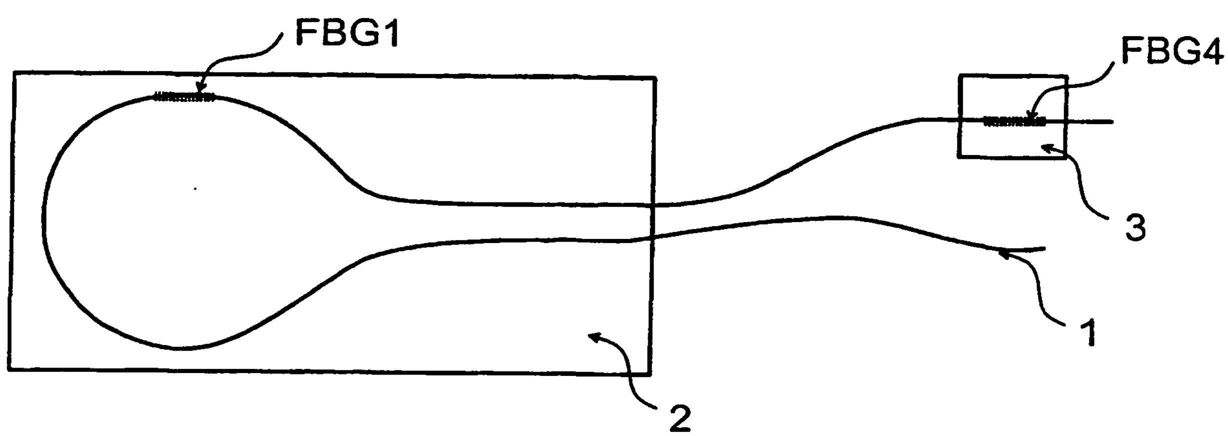

FIG. 1A

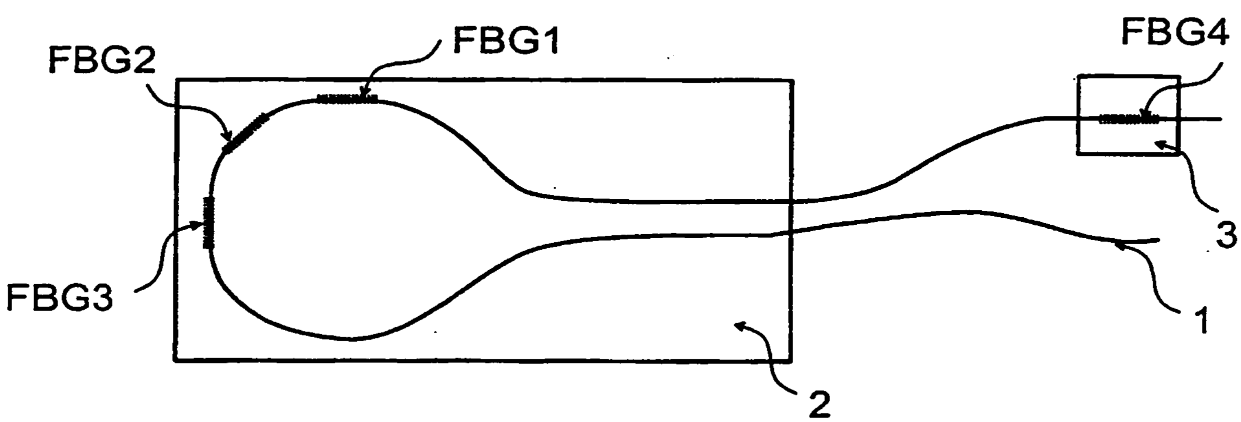

FIG. 1B

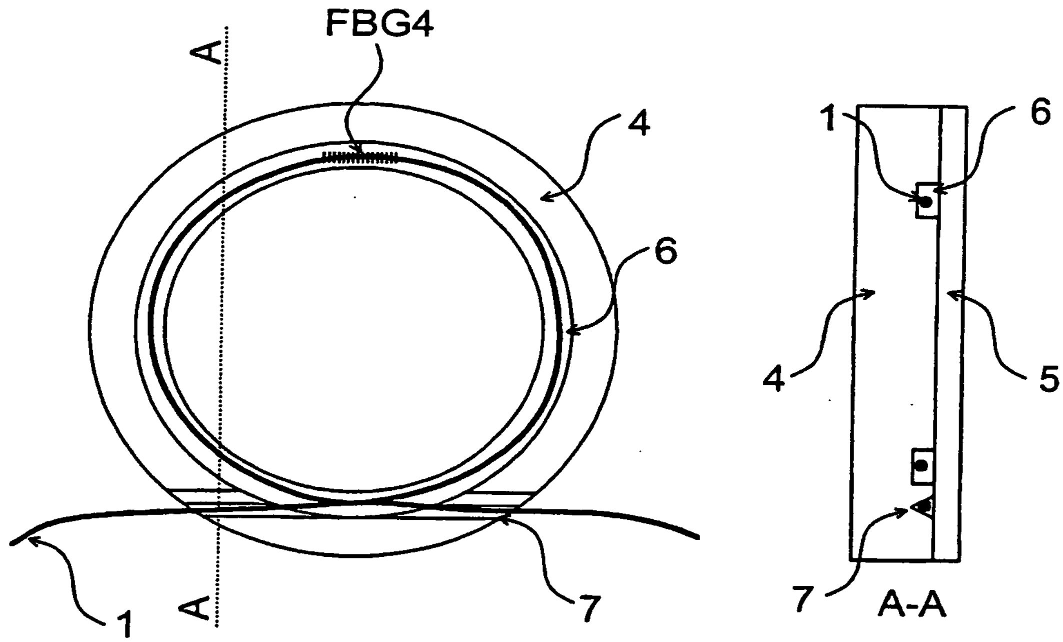

FIG. 2A

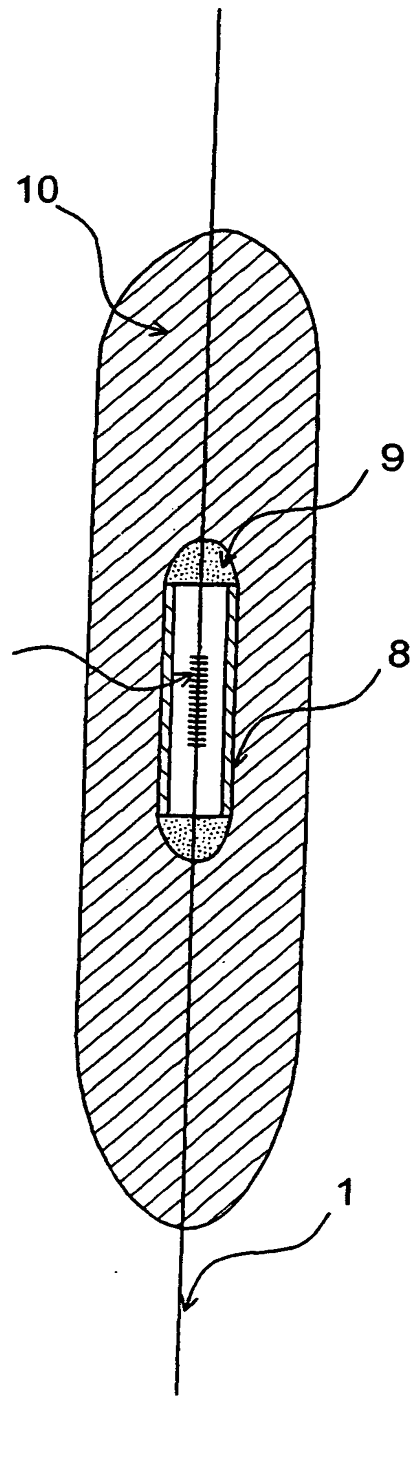

FIG. 2B

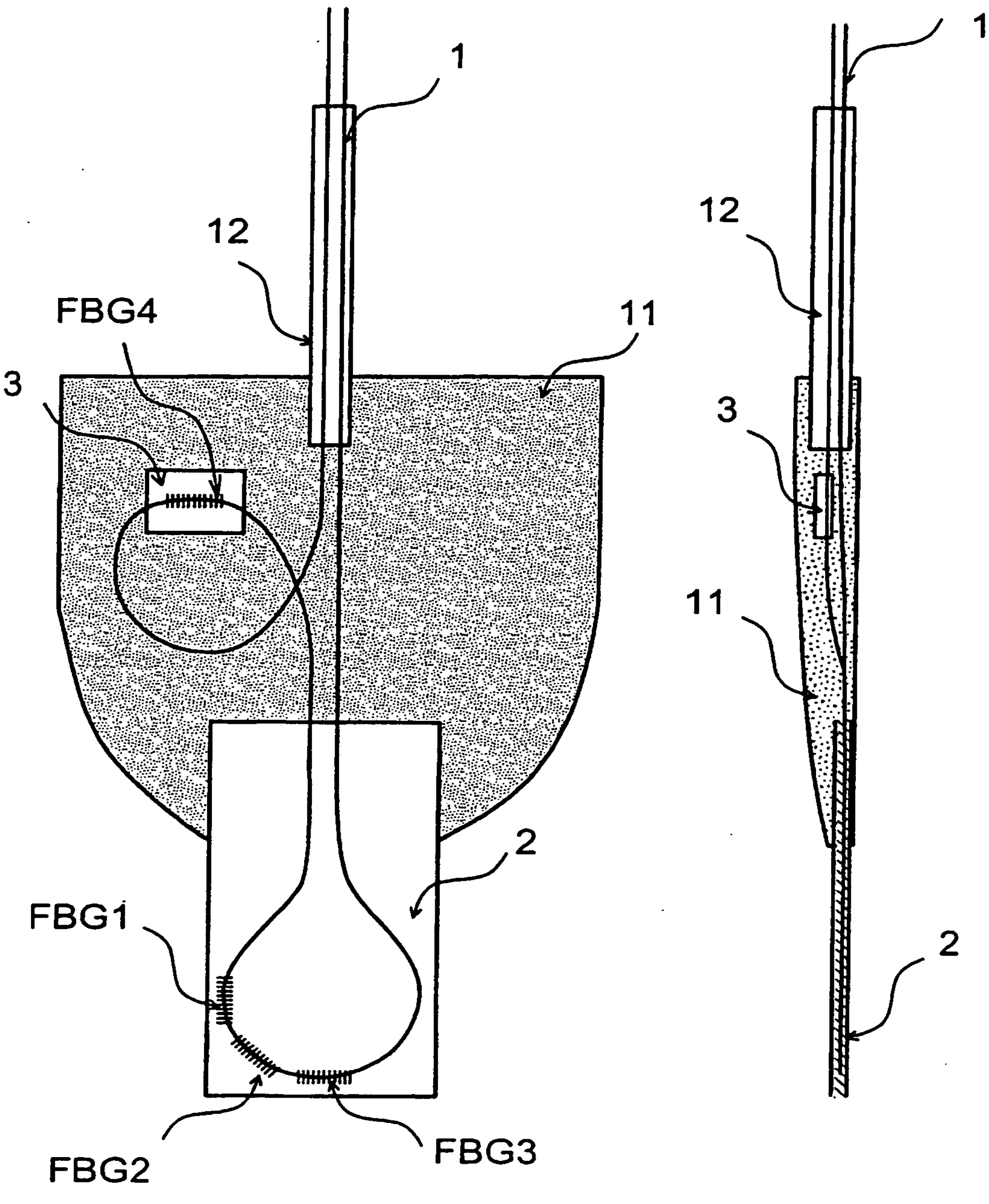

FIG. 3

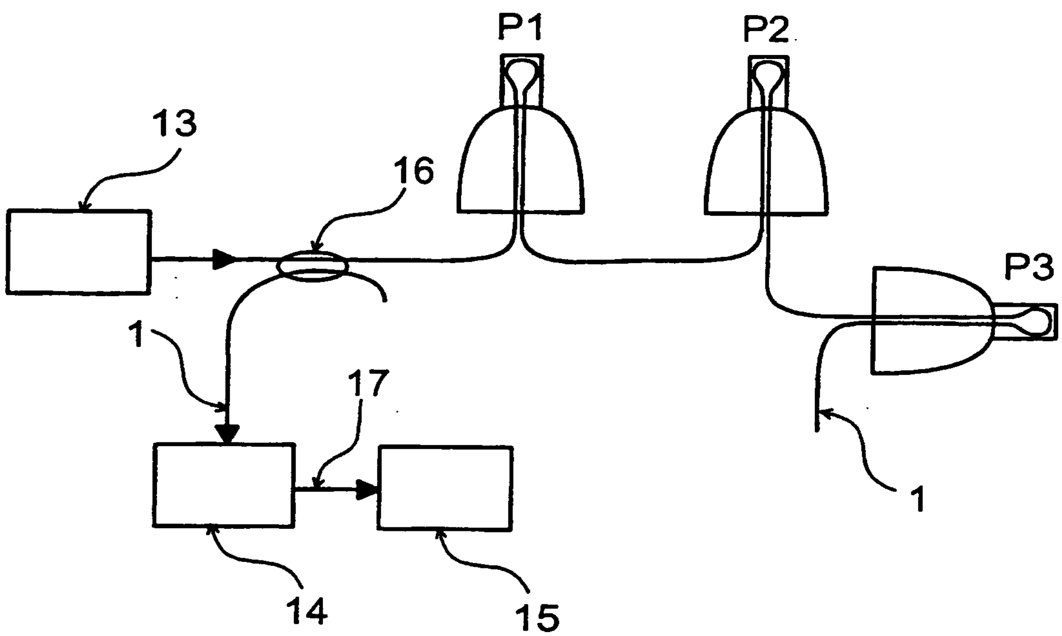

FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01K11/32 G01L1/24 G01D5/353

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01K G01L G01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 1 148 324 A (NTT ADVANCED TECH KK) 24 October 2001 (2001-10-24) the whole document ---	1-5,8-16
Y	US 5 726 744 A (MAGNE SYLVAIN ET AL) 10 March 1998 (1998-03-10) the whole document ---	1-4,8-16
Y	US 6 125 216 A (FOOTE PETER D ET AL) 26 September 2000 (2000-09-26) the whole document ---	5,8,14
Y	US 5 973 317 A (HAY ARTHUR D) 26 October 1999 (1999-10-26) column 5, line 13 - line 20; figure 3 --- -/--	6,12

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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	International Application No
INTERNATIONAL SEARCH REPORT	PCT/NO 03/00087

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	WO 00 39548 A (CIDRA CORP) 6 July 2000 (2000-07-06) figure 1	7
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